

Photoinduced dynamics in quantum rings

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We investigate the spin-dependent dynamical response of a semiconductor quantum ring with a spin orbit interaction (SOI) upon the application of a single and two linearly polarized, picosecond, asymmetric electromagnetic pulses in the presence of a static magnetic flux. We find that the pulse-generated electric dipole moment (DM) is spin dependent. It is also shown that the SOI induces an extra SU(2) effective flux in addition to the static external magnetic flux which is reflected in an additional periodicity of the spin-dependent DM. Furthermore, the pulses may induce a net dynamical charge currents (CC) and dynamical spin currents (SC) when the clockwise and anti-clockwise symmetry of the carrier is broken upon the pulse application.

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INTRODUCTION

Spin-orbit interaction (SOI) in semiconducting low dimensional structures is a key factor for spintronic research [1]. There are two important kinds of SOI in conventional semiconductors: one is the Dresselhaus SOI induced by bulk inversion asymmetry [2], and the other is the Rashba SOI caused by structure inversion asymmetry [3]. As pointed out in [4], the Rashba SOI is dominant in a narrow gap semiconductor and the strength of it can be tuned by an external gate voltage [5]. This tunability of the magnitude of the Rashba SOI is crucial for the operation of spintronics device such as the spin field effect transistor [6] and the spin interference device [7].

In this work we are interested in quantum rings (QR) [8] which are synthesized routinely with current nanotechnology. Available phase-coherent rings vary in a wide range in size and particle density [9]. On the theoretical side, the equilibrium properties of QRs are fairly understood and documented [8]. Current focus is on the non-equilibrium dynamics, in particular that driven by external time-dependent electromagnetic fields [10, 11]. E.g., it has been shown that the irradiation with picosecond (from a few hundreds femtoseconds up to nanoseconds, typically picosecond [12]), time-asymmetric, low-intensity light fields generates charge polarization and charge currents in the ring. A particular feature of the driving pulse is that the electric field has a short half cycle followed by a much longer and weaker half cycle of an opposite polarity. Such pulses are called half-cycle pulse (HCP) because, under certain conditions, only the very short and strong half optical cycle is decisive for the carrier dynamics.

Here we study QRs as those fabricated out of a two dimensional electron gas formed between heterojunctions of III-V and II-VI semiconductors. The influence of the SOI in QRs on the equilibrium properties have already been studied [13, 14]. In this work, we shall consider the spin-dependent *non-equilibrium* dynamic of the ring with SOI driven by HCP's and in the presence of a magnetic

flux. We investigate two cases: applying single pulse and two time-delayed pulses with non-collinear polarization axes.

THEORETICAL MODEL

Hamiltonian

For effective single particle Hamiltonian of a one-dimensional (1D) ballistic QR with SOI we use $\hat{H}' = \hat{H}_{\text{SOI}} + \hat{H}_1(t)$ [13], with

$$\begin{aligned}\hat{H}_{\text{SOI}} &= \frac{\mathbf{p}^2}{2m^*} + V(\mathbf{r}) + \frac{\alpha_R}{\hbar}(\hat{\sigma} \times \mathbf{p})_z, \\ \hat{H}_1(t) &= -e\mathbf{r} \cdot \mathbf{E}(t) + \mu_B \mathbf{B}(t) \cdot \hat{\sigma}.\end{aligned}\quad (1)$$

where α_R is the SOI parameter, $V(\mathbf{r})$ is confinement potential, $\mathbf{E}(t)$ and $\mathbf{B}(t)$ are the electric and the magnetic fields of the pulse. Integrating out the r dependence \hat{H}_{SOI} reads in cylindrical coordinates [13, 14]

$$\hat{H}_{\text{SOI}} = \frac{\hbar\omega_0}{2} \left[\left(i\frac{\partial}{\partial\varphi} + \frac{\phi}{\phi_0} - \frac{\omega_R}{2\omega_0}\sigma_r \right)^2 - \left(\frac{\omega_R}{2\omega_0} \right)^2 + \frac{\omega_B}{\omega_0}\sigma_z \right]. \quad (2)$$

$\phi_0 = h/e$ is the flux unit, $\phi = B\pi a^2$ is the magnetic flux, a is the radius of the ring, $\sigma_r = \sigma_x \cos \varphi + \sigma_y \sin \varphi$, $\hbar\omega_0 = \hbar^2/(m^*a^2) = 2E_0$, $\hbar\omega_R = 2\alpha_R/a$, $\hbar\omega_B = 2\mu_B B$ and an external static magnetic field $\mathbf{B} = B\hat{\mathbf{e}}_z$.

The single-particle eigenstates of \hat{H}_{SOI} are represented as $\Psi_n^S(\varphi) = e^{i(n+1/2)\varphi} \nu^S(\gamma, \varphi)$ where $\nu^S(\gamma, \varphi) = (a^S e^{-i\varphi/2}, b^S e^{i\varphi/2})^T$ (T means transposed) are spinors in the angle dependent local frame, and $a^\dagger = \cos(\gamma/2)$, $b^\dagger = \sin(\gamma/2)$, $a^\downarrow = -\sin(\gamma/2)$, $b^\downarrow = \cos(\gamma/2)$, where $\tan \gamma = -Q_R = -\omega_R/\omega_0$ (we ignore the Zeeman splitting). γ describes the direction of the spin quantization axis. The energy spectrum of the QR with the SOI reads $E_n^S = \frac{\hbar\omega_0}{2} \left[\left(n - \frac{\phi}{\phi_0} + \frac{1-Sw}{2} \right)^2 - \frac{Q_R^2}{4} \right]$, where $w = \sqrt{1 + Q_R^2} = 1/\cos \gamma$, and $S = \pm 1$ stands for spin up (down) in the local frame.

Time-dependent wave functions

At first we apply a single HCP pulse at $t = 0$. The pulse propagates in the z direction and has a duration τ_d . Its E-field is along the x axis. When two pulses are applied, the first pulse is followed by a second one at $t = \tau$ with the same duration but the E-field being along the y axis. We consider the case where τ_d is much shorter than the ballistic time of the QR carriers. The single particle states develop then as [11]

$$\begin{aligned}\Psi_n^S(\varphi, t > 0) &= \Psi_n^S(\varphi, t < 0)e^{i\alpha_1 \cos \varphi}, \\ \Psi_{n_0}^{S_0}(\varphi, t > \tau) &= \Psi_{n_0}^{S_0}(\varphi, t < \tau)e^{i\alpha_2 \sin \varphi}, \\ \alpha_{1(2)} &= \frac{eap_{1(2)}}{\hbar}, \quad p_{1(2)} = -\int_0^{\tau_d} E_{1(2)}(t)dt, \\ E_{1(2)}(t) &= F_{1(2)}f(t).\end{aligned}\quad (3)$$

$F_{1(2)}$ and $f(t)$ describe the amplitude and the time dependence of the E-field of the first (second) pulse respectively. The pulse effect is encapsulated entirely in the *action parameter* $\alpha_{1(2)}$. With the initial conditions $n(t < 0) = n_0$ and $S(t < 0) = S_0$ one finds

$$\Psi_{n_0}^{S_0}(\varphi, t) = \sum_{ns} \frac{C_n^S(n_0 S_0 t)}{\sqrt{2\pi}} e^{i(n+1/2)\varphi} e^{-iE_n^S t/\hbar} |\nu^S\rangle, \quad (4)$$

with

$$C_n^S = \begin{cases} \delta_{SS_0} \delta_{nn_0} & \text{for } t \leq 0, \\ \delta_{SS_0} i^{n_0-n} J_{n_0-n}(\alpha_1) & \text{for } t \in [0, \tau), \\ \sum_{n'} \Lambda_{nn'n_0}^{SS_0} e^{i(E_n^S - E_{n'}^{S_0})\tau/\hbar} & \text{for } t > \tau, \end{cases} \quad (5)$$

where $\Lambda_{nn'n_0}^{SS_0} = \delta_{SS_0} [i^{n_0-n'} J_{n_0-n'}(\alpha_1) J_{n-n'}(\alpha_2)]$ and J_n is the n -th order Bessel function.

NUMERICAL RESULTS AND DISCUSSIONS

Single pulse case

One HCP pulse induces dynamical oscillation of charge density which is manifested as an electrical dipole moment $\mu_{n_0}^{S_0}(t) = ea \langle \cos \varphi \rangle_{n_0}^{S_0}(t)$, where $\langle \cos \varphi \rangle_{n_0}^{S_0}(t) = \int_0^{2\pi} d\varphi |\Psi_{n_0}^{S_0}(\varphi, t)|^2 \cos \varphi$. The total dipole moment can be derived by summation over all the occupied states. In the presence of the SOI, the dipole moment splits with respect to different spin states. Fig. 1 shows a contour plot of the difference of the dipole moments (in units of ea) for the up and down spins which varies with the magnetic flux and the SOI. The distinct positive and negative regions correspond to the local spatial splitting of carrier density for up and down spin states. The oscillation with the static magnetic flux are observed, as expected.

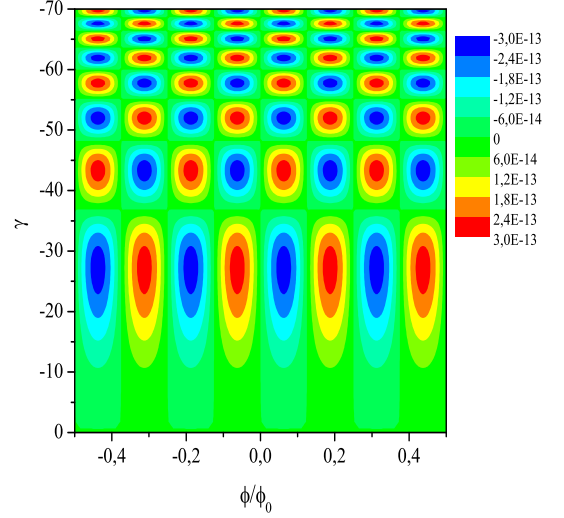


FIG. 1: Contour plot of the difference of the dipole moment for up and down spins at the time moment $t/t_p = 2$ (t_p is the ballistic (field-free) round trip time). The particle number is $N = 100$ and the pulse properties are described by the dimensionless parameter $\alpha_1 = 0.1$ (cf. eq.(3)).

The oscillation with the SOI angle γ are such, larger γ leads to shorter period oscillations. Increasing γ induces a shift of the oscillation frequencies. However, increasing the strength of the laser field brings more excited energy levels and more frequencies.

Two pulses case

The charge current (CC) and the spin current (SC) are calculated [15] using the velocity operator $\hat{\mathbf{v}}_\varphi = \hat{\mathbf{e}}_\varphi \left\{ \frac{-i\hbar}{m^*a} \partial_\varphi - \frac{\hbar}{m^*a} \frac{\phi}{\phi_0} + \frac{\alpha_B}{\hbar} \sigma_r \right\}$. The SOI induces a SU(2) vector potential (VP) appearing as the third term in the velocity operator. The static magnetic flux and SU(2) VP generate spin independent and spin-dependent persistent charge current (PCC) respectively even in the absence of the pulse field. The laser pulse triggers dynamic CC and SC which are tunable by external parameters. Therefore, the total CC (TCC) and the total SC (TSC) (sum over the persistent and dynamic components) for up and down spins are investigated in Fig. 2 with the delay time τ .

It is clear, with the appropriate τ , positive and negative TCC can be obtained. TSC for up and down spins are also oscillating and decaying with larger τ . However TSC shows opposite phase with respect to up and down spin states. If $\phi = 0$, the SOI gives rise to equal shifts for up and down spin states but in opposite directions, mak-

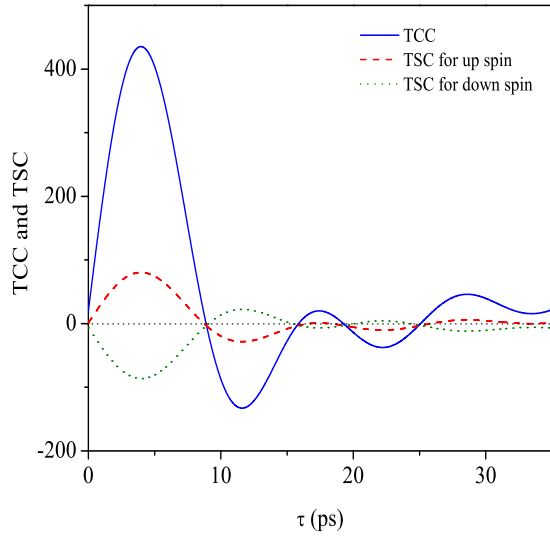


FIG. 2: TCC and TSC vary with the delay time τ . The units for CC and SC are $2E_0a/\phi_0$ and $E_0a/2\pi$ respectively. The parameters are $N = 100$, $a = 400\text{nm}$, $\gamma = -40^\circ$, $F_1 = F_2 = 500\text{V/cm}$ and $\phi/\phi_0 = 0.3$.

ing the TSC exactly reverse to each other. If $\phi \neq 0$, the two components of TSC are not exactly opposite, which corresponds to a slight imbalance occupation for up and down spin states. More analysis of the behavior of the system driven by the HCP pulse can be found in Ref. [15].

In summary, it is shown that asymmetric electromagnetic pulses can be used to generate and control spin-dependent charge oscillation and dynamic currents in nano- and mesoscopic rings.

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